REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
13-11-2003

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Integration of InfraMAP with Near-Real-Time Atmospheric Characterizations and Applications to Infrasound Modeling

5a. CONTRACT NUMBER
DTRA01-01-C-0084

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
DTRA

5e. TASK NUMBER
01

5f. WORK UNIT NUMBER
A1

6. AUTHOR(S)
R. G. Gibson and D. E. Norris

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
BBN Technologies
1300 North 17th Street
Arlington, VA 22209

8. PERFORMING ORGANIZATION REPORT

20031126 111

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB MA 01731-3010

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSBYE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-VS-TR-2003-1609

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
REPRINTED FROM: PROCEEDINGS OF THE 25TH SEISMIC RESEARCH REVIEW - NUCLEAR EXPLOSION MONITORING 'BUILDING THE KNOWLEDGE BASE', 23-25 September 2003, Tucson, AZ, Vol II, pp 638-645

14. ABSTRACT
The primary objective of this research effort is development of an enhanced InfraMAP software tool kit that enables higher-fidelity infrasound propagation modeling by incorporating near-real-time atmospheric characterizations. This effort is intended to support improved event localization and phase identification. A validation effort is also being undertaken, using a diverse set of observations and ground-truth, in order to improve confidence in the modeling techniques and provide calibration in support of operational needs. Anticipated uses of the software include: in-depth analysis of events and scenarios of particular monitoring interest; sensitivity analyses; and detailed infrasound localization and detection studies.

15. SUBJECT TERMS
Infrasound   Infrasound propagation   Atmospheric models

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	8	Robert Raistrick
					19b. TELEPHONE NUMBER *(include area code)* 781-377-3726

INTEGRATION OF INFRAMAP WITH NEAR-REAL-TIME ATMOSPHERIC CHARACTERIZATIONS AND APPLICATIONS TO INFRASOUND MODELING

Robert G. Gibson and David E. Norris

BBN Technologies

Sponsored by Air Force Research Laboratory

Contract No. DTRA01-01-C-0084

ABSTRACT

Predicting the long-range propagation of infrasound relies on characterization of the propagation medium, namely the global atmosphere from the ground to altitudes above 100 km. The ability to realistically model infrasound propagation depends on the fidelity of the atmospheric characterization. The analysis tool kit InfraMAP (*Infra*sound *M*odeling of *A*tmospheric *P*ropagation) offers a range of options for specifying the propagation environment. The baseline capability utilizes global climatological models of temperature, wind and air composition. Of particular interest herein is the recently developed capability to incorporate near-real-time atmospheric updates, such as the output from numerical weather prediction models, to supplement climatological characterization of the environment.

New InfraMAP modules support integration of propagation models (ray-tracing, parabolic equation) with two versions of near-real-time atmospheric characterizations. First, output from the Navy's synoptic model NOGAPS (Navy Operational Global Atmospheric Prediction System) can be imported into InfraMAP and merged with the baseline climatological models, HWM-93 and NRL-MSISE-00. NOGAPS generates global grids of temperature and wind, several times per day, on a one-degree grid over 27 isobaric surfaces. The corresponding altitudes are not sufficiently high to characterize the entire region of interest for infrasound propagation; therefore, NOGAPS output is merged with climatology within InfraMAP at the higher altitudes to cover the full propagation domain. Second, output from the NRL-G2S (Naval Research Laboratory Ground to Space) specification can be imported and used to characterize the entire propagation environment. NRL-G2S is a semi-empirical spectral model that fuses climatological models with output from operational numerical weather prediction models. These new capabilities extend the ability of infrasound researchers to investigate critical propagation phenomena and to conduct sensitivity studies.

Validation efforts are essential to build confidence in the modeling procedures and are used to assess the value of potential improvements to the atmospheric specification. Observed infrasound events with known ground truth represent valuable sources of opportunity for use in validating propagation modeling techniques. InfraMAP has been used to model long-range propagation of infrasound originating from the space shuttle and other sources. Predictions of infrasound arrival times and azimuths resulting from three-dimensional ray tracing through various environments are compared with observed data.

OBJECTIVES

The primary objective of this research effort is development of an enhanced InfraMAP software tool kit that enables higher-fidelity infrasound propagation modeling by incorporating near-real-time atmospheric characterizations. This effort is intended to support improved event localization and phase identification. A validation effort is also being undertaken, using a diverse set of observations and ground-truth, in order to improve confidence in the modeling techniques and provide calibration in support of operational needs. Anticipated uses of the software include: in-depth analysis of events and scenarios of particular monitoring interest; sensitivity analyses; and detailed infrasound localization and detection studies.

RESEARCH ACCOMPLISHED

Near-Real-Time Environmental Updates to InfraMAP

The InfraMAP software tool kit is composed of research-grade propagation models (3-D ray tracing, normal modes and parabolic equation) and upper-atmospheric characterizations, integrated to allow for user-friendly model execution and data visualization. InfraMAP can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide. Such predictions can be used to identify infrasound phases and to define travel-time and bearing corrections, which can improve localization performance (Gibson and Norris, 2002a). Recently introduced InfraMAP modules allow for analysis of propagation variability due to environmental effects, calculation of source location using measurements and model predictions, and prediction of network localization performance (Norris and Gibson, 2002).

Range-dependent characterizations of temperature, wind and air composition are incorporated into the propagation models to account for temporal and spatial variability of the atmosphere. The baseline atmospheric characterizations in InfraMAP are two empirical models: the horizontal wind model, HWM-93 (Hedin *et al.*, 1996), and the mass spectrometer-incoherent scatter radar extended model, NRLMSISE-00, which provides temperature and air composition (http://uap-www.nrl.navy.mil/models_web/msis/msis_home.htm). The integration of the NRLMSISE-00 model into InfraMAP is a recent upgrade from the earlier baseline temperature model, MSISE-90 (Picone *et al.*, 1997). Using these characterizations, wind, temperature, and molecular densities are modeled from the surface into the thermosphere and include spatial, diurnal, and seasonal effects. The models are climatological in that they predict the mean environmental profiles based on assimilation of multiple years of data.

The HWM and MSISE models were chosen for use in InfraMAP due to their high fidelity over a wide range of altitudes and temporal scales, their global domain, and the relative ease of software integration. Validation studies conducted to date using InfraMAP with the HWM and MSISE characterizations indicate generally good agreement between modeled propagation paths and infrasound measurements. However, there exist cases in which measured infrasound phases are not adequately predicted using the baseline InfraMAP. Global climatological models such as HWM and MSISE that are based solely on historical data do not capture fine-scale temporal and spatial atmospheric structure. The current effort addresses the incorporation of appropriate near-real-time sources of atmospheric information to improve the estimate of the infrasound propagation environment.

Classes of near-real-time atmospheric updates include:

- *in situ* observations, such as measured profiles from radiosondes, and
- physics-based synoptic models that assimilate observations from a number of sources.

Models generally produce gridded output, whereas observed profiles (e.g., radiosondes) are not gridded, i.e., the observations are not uniformly sampled geographically or in altitude. InfraMAP allows for integration of *in situ* data sources with range-independent propagation modeling by providing an option for manually importing user-defined atmospheric profiles. The focus of activity during this effort has been on the integration of output from synoptic models with InfraMAP.

New InfraMAP modules have been developed to incorporate output from the Navy Operational Global Atmospheric Prediction System (NOGAPS), which provides near-real-time global grids of temperature and wind over three spatial dimensions (Bayler and Lewit, 1992). NOGAPS, originated by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC), is a numerical weather prediction system that utilizes not only profiles measured by radiosondes, but also an extensive data set of ship-based, land-based and satellite measurements. It provides

temperature and wind speed, several times per day, on a one-degree grid over 27 isobaric surfaces. Output data from NOGAPS are readily available from the ground up to the 10 mb pressure surface (approx. 30-35 km).

Figures 1a and 1b show examples of temperatures along a slice of the atmosphere between the South Pole and the North Pole, at a constant longitude, from NRLMSISE-00 and NOGAPS, respectively, for a particular day and time. The large-scale temperature features are similar between the climatology and the near-real-time characterization, but the fine-scale structure is different. It can also be observed that the NOGAPS grid is non-uniform in altitude, due to the use of pressure surfaces rather than constant altitude surfaces. The upper boundary of the NOGAPS grid can be seen, varying between approximately 27 and 33 km in this case.

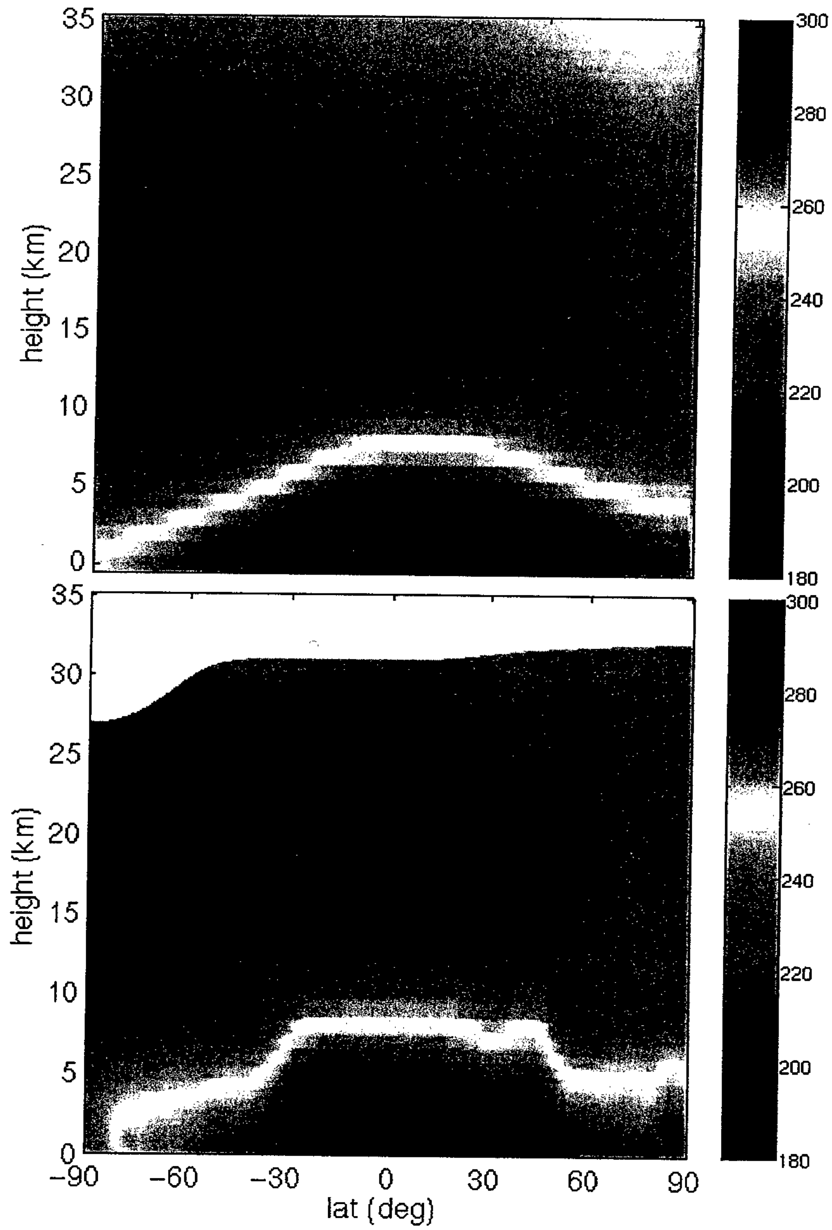

Figure 1a (above) and 1b (below). Temperatures (in degrees K) from NRLMSISE-00 climatology (above) and NOGAPS numerical weather prediction model (below), along a slice of the atmosphere at constant longitude of 60 degrees W, for Year 1999, Day 206, 0 UT.

An additional example is presented in Figures 2a and 2b, which show zonal winds over a region between the equator and the North Pole (in a Mercator-style projection), from HWM-93 and NOGAPS, respectively, for a particular day and time (29 September 2002). In the HWM figure, winds are shown at a constant altitude of 30 km. In the NOGAPS figure, winds are shown at the 10 mb constant pressure surface, which is at a slowly varying altitude of approximately 30 km throughout the region. The large-scale features are similar in the two figures, showing a shift in wind direction with increasing latitude. However, there is considerably more fine-scale structure in the NOGAPS characterization.

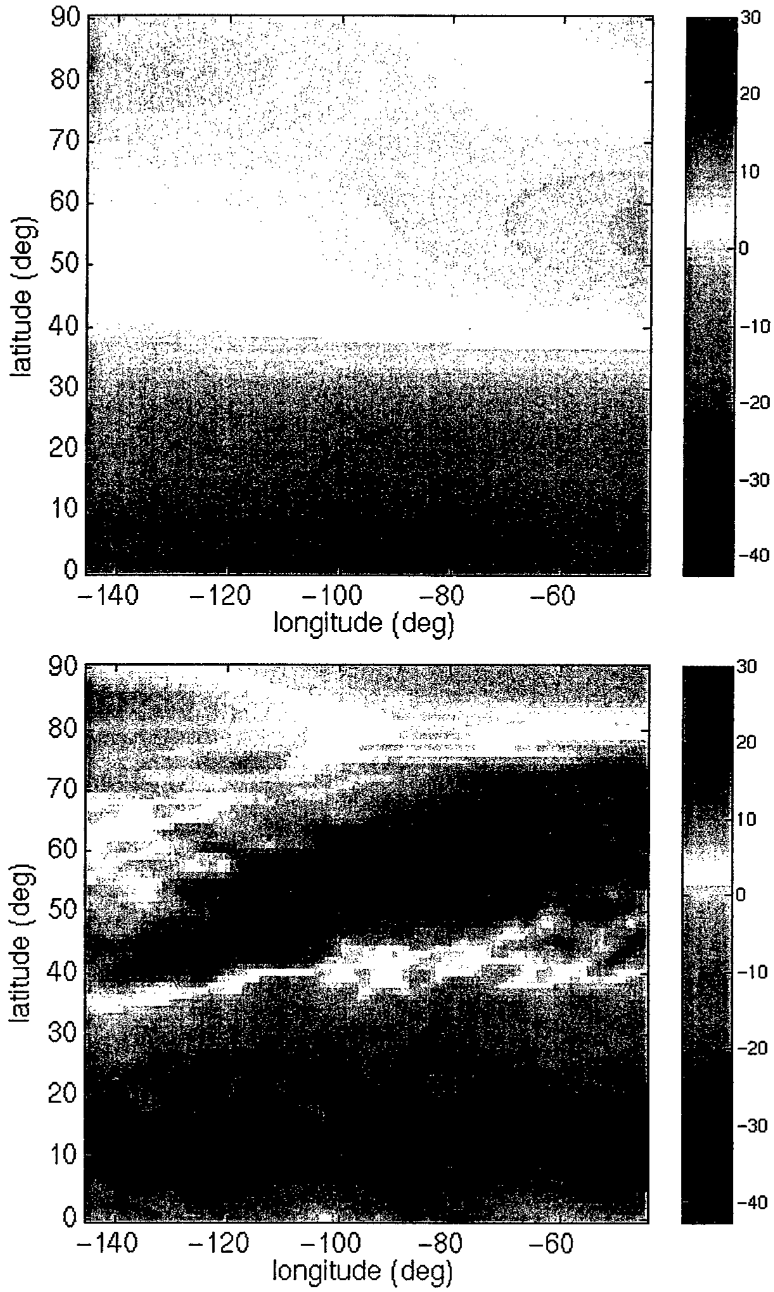

Figure 2a (above) and 2b (below). Zonal winds (in meters per second) from HWM-93 climatology (above) and NOGAPS numerical weather prediction model (below), above a region of the northern hemisphere at constant altitude of 30 km (above) and constant pressure surface of 10 mb (below), for Year 2002, Day 272, 0 UT.

NOGAPS is a promising environmental characterization for use with infrasound propagation models due to its global domain, frequent updates, and relatively high altitude coverage. However, infrasound propagation modeling requires information well into the thermosphere (approx. 120 km). Therefore, climatological models remain an essential tool for estimating the environment, particularly at high altitudes. Techniques have been developed within InfraMAP to merge NOGAPS grids at lower altitudes with climatological models at higher altitudes.

Links have been implemented to archives of NOGAPS grids, and modules have been developed to import and decode the files for use in InfraMAP. A user then selects a subset of the global grid (i.e., a range of latitude and longitude cells) for use in a propagation scenario of interest. Within the region of interest, NOGAPS output is used in conjunction with the HWM and MSISE characterizations to define the propagation environment. A user specifies the thickness of the transition layer above NOGAPS. A cubic interpolation algorithm that matches the values and their derivatives at the boundaries is employed to join NOGAPS temperatures, zonal winds and meridional winds with the climatologies. This approach results in smooth first derivatives and continuous second derivatives, which ensures that non-physical behavior is not introduced in the ray path predictions. Examples of resulting temperature profiles are shown in Figure 3. Four profiles are shown for locations at the corners of a specified region. The transition region in this case is 10 km in thickness.

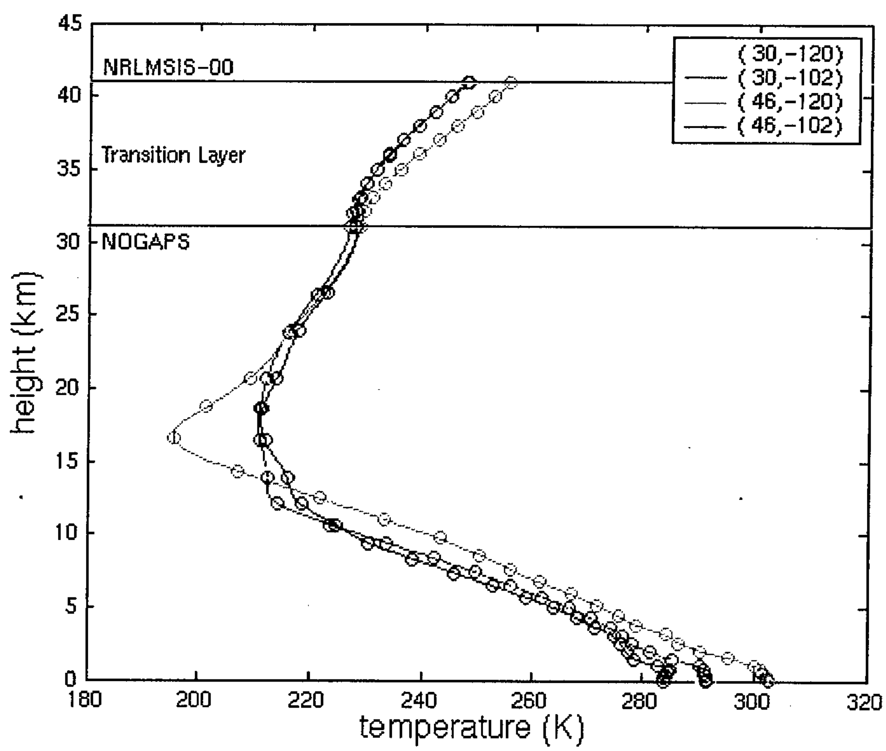

Figure 3. Temperature profiles (in degrees K) at four locations over North America, from InfraMAP. NOGAPS numerical weather prediction model is used at lower altitudes and NRLMSISE-00 climatology is used at higher altitudes, with a transition region between. Year 2002, Day 272, 0 UT.

NOGAPS characterizations can be viewed in InfraMAP's environmental menu and can be used in propagation modeling. In order to accommodate an environment defined by a gridded database such as NOGAPS, modifications have been made to InfraMAP's interface between propagation codes and environmental characterizations, particularly in order to allow range dependence. To propagate three-dimensional rays through gridded data, wind and temperature values and their spatial derivatives must be estimated at each point along a ray path. Because ray models are highly sensitive to sharp changes in sound speed, the estimation approach must avoid introducing gradient variability that is not inherent in the original data grid.

InfraMAP is also being upgraded to incorporate an additional near-real-time atmospheric characterization. Output from the NRL-G2S (Naval Research Laboratory Ground to Space) specification can be used to characterize the entire propagation environment. NRL-G2S is a semi-empirical spectral model that fuses climatological models with output from operational numerical weather prediction models (Drob and Garces, 2002). Upper atmospheric characterizations are based on NRLMSISE-00 and HWM-93. Lower atmospheric characterizations are based not only on NOGAPS but also on output of other prediction systems and other relevant global data sets. NRL-G2S employs vector spherical harmonics in the data assimilation process to produce a set of model coefficients for each day and time of interest. Coefficient sets can then be used to reconstruct fields of each atmospheric state variable as well as spatial derivatives. An InfraMAP user can access coefficient sets from a data repository, import the coefficients, and utilize the resulting NRL-G2S specifications within InfraMAP to define a propagation environment.

Supplementing the baseline climatological models with available near-real-time updates is likely to yield improved infrasound predictions, particularly for propagation paths that dwell primarily in the lower and middle atmosphere, where updated data are more readily available.

Other Enhancements to Environmental Specifications in InfraMAP

In addition to the incorporation of NRLMSISE-00, NOGAPS and NRL-G2S specifications, a number of other enhancements have been introduced in InfraMAP to improve the fidelity of the environmental characterization. They include:

- Integrated archive of solar and geomagnetic parameters;
- Incorporation of variable molecular weight in sound velocity calculations;
- Incorporation of variable specific heat ratio in sound velocity calculations.

These are primarily intended to improve characterization of the thermosphere.

Solar flux and geomagnetic disturbances from solar activity influence the modeled atmospheric temperature and winds above 100 km and have been shown to affect the modeled propagation of thermospheric infrasound (Gibson and Norris, 2002a). The variables F10.7, F10.7A, and A_P are used as input to the HWM and MSISE models, and entry of values for these parameters allows their effects to be modeled in InfraMAP.

- A_P is the planetary equivalent amplitude of daily geomagnetic disturbance,
- F10.7 is the daily solar radio flux at 10.7 cm wavelength, and
- F10.7A is the 81 day average of F10.7 values, centered on the day of interest.

Archives of historical values, obtained from the National Geophysical Data Center (NGDC), have been integrated in InfraMAP, and appropriate daily values are automatically selected as defaults in a propagation run. Daily values of the parameter A_P for the year 2001 are shown in Figure 4a. Temperatures from MSISE, calculated for a range of thermospheric altitudes above the North Pole, are shown in Figure 4b for a representative range of A_P values.

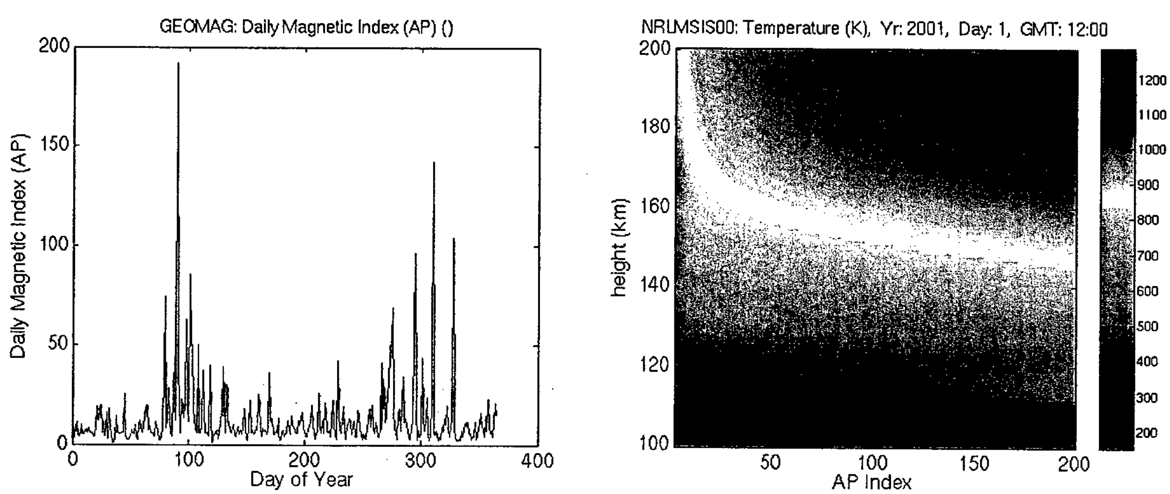

Figure 4a (left) and 4b (right). Daily values of geomagnetic disturbance parameter A_P for year 2001 (left) and thermospheric temperatures above the North Pole for a range of A_P, using NRLMSISE-00 (right).

The values of the average molecular weight and the specific heat ratio (the ratio of heat capacity at constant pressure to heat capacity at constant volume), both of which depend on air composition, have effects on calculations of sound velocity and acoustic absorption. The determination of these quantities using NRLMSISE-00 has recently been included in InfraMAP calculations. This will improve fidelity of the modeling of thermospheric infrasound at little or no computational cost. Examples of typical ranges of these parameters over the annual cycle, as predicted from MSISE, are shown in Figures 5a and 5b.

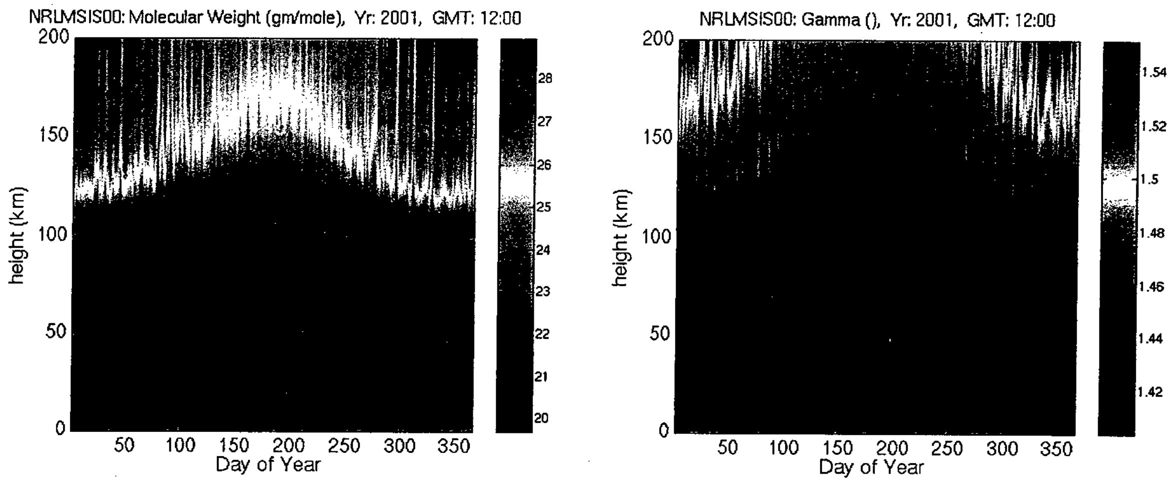

Figure 5a (left) and 5b (right). Modeled values of average molecular weight (in grams/mole, at left) and specific heat ratio (dimensionless, at right) at a range of altitudes above the North Pole, calculated using NRLMSISE-00 over the annual cycle. The "spiky" features result from incorporation of the solar and geomagnetic measurements for the year 2001 (as shown in Figure 4a).

Software Integration

The near-real-time update capabilities developed to date and other environmental enhancements have been integrated into the InfraMAP software tool kit, and graphical user interfaces have been developed. User manual development and software beta testing are in progress. The most recent software release, InfraMAP 3.0, developed under a parallel effort (Norris and Gibson, 2002), will be upgraded in a subsequent release as part of this effort.

Model Validation Efforts

Validation efforts are essential to build confidence in the modeling procedures and to identify areas where further refinements are required. Where ground-truth is available, validation results support event localization, phase identification and calibration efforts.

Validation activities during this effort have focused on infrasound from rocket launches. Space shuttle launches from Cape Kennedy, FL have been frequently observed at infrasound arrays at Los Alamos, NM (DLIAR prototype array), at Lac du Bonnet, Canada (IS10 array), and at other locations in the eastern US. Reasonably good agreement in both travel time and azimuth has been obtained between ray tracing model results using InfraMAP and observed infrasound, and biases have been quantified for individual events (Gibson and Norris, 2002b). Components of infrasound signals have been associated with both the ascending orbiter and the descending solid rocket boosters. More recently, analyses have been conducted of annual trends in observability, travel time and azimuth of infrasound signals from space shuttle launches (Gibson and Norris, 2002c). Preliminary investigations have also been conducted into the improvements in model fidelity that are achievable using NOGAPS environmental updates. These investigations are ongoing and will focus on first establishing a baseline and then documenting the modeling improvements achievable with near-real-time updates as compared to climatology.

Based on the successful model results previously obtained for space shuttle launches, the authors participated in the Department of Defense Columbia Investigation Support Team (DCIST) Infrasound Working Group (ed. Bass, 2003). InfraMAP was used to model infrasound from the reentry and approach of the space shuttle Columbia up to the point of its untimely breakup. During this investigation, the NRL-G2S specifications were used to characterize the propagation environment. Range-independent propagation modeling was conducted from a large number of points along the reentry trajectory to the locations of those infrasound arrays in the western US and Canada that observed the event. Ray tracing model predictions of arrival time, azimuth and elevation angle were generally in good agreement with the observations.

CONCLUSIONS AND RECOMMENDATIONS

The InfraMAP tool kit is used to predict the critical propagation characteristics that affect infrasound localization and detection. Adequate atmospheric characterization is necessary to correct for biases in travel time and azimuth that result from the propagation environment in order to avoid large location errors. *In situ* observations of winds and temperature can be used in InfraMAP for range-independent propagation modeling. Techniques have been developed to integrate output from the NOGAPS numerical weather prediction model with climatology for use in range-dependent propagation models. The NRL-G2S atmospheric specifications can also be used within InfraMAP. InfraMAP's integrated set of models will allow for higher fidelity propagation modeling than has previously been available to the infrasound monitoring community. As new high-fidelity environmental characterizations become available, they should be considered for integration into an enhanced version of the InfraMAP software.

Rocket launches and reentries generate infrasound signals for use in model validation studies. Comparisons of measured and modeled arrival times and azimuths suggest that baseline infrasound modeling techniques are good but that higher fidelity predictions would likely be obtained with the use of near-real-time wind and temperature characterizations. Further modeling of a large set of observed events, using updated atmospheric characterizations, should continue in order to quantify the improvements in travel time and azimuth predictions that are achievable.

REFERENCES

Bayler, G. and H. Lewit (1992), The Navy Operational Global and Regional Atmospheric Prediction System at the Fleet Numerical Oceanography Center, *Weather and Forecasting*, Vol. 7, No. 2.

Drob, D. P. and M. Garces (2002), The spatiotemporal variability of infrasound path partitioning, *Proceedings of the Infrasound Technology Workshop*, De Bilt, NL.

Gibson, R. and D. Norris (2002a), Development of an Infrasound Propagation Modeling Tool Kit, DTRA-TR-99-47.

Gibson, R. G. and D. E. Norris (2002b), Integration of near-real-time atmospheric models with InfraMAP and applications to modeling infrasound from rockets, *Proceedings of the 24th Seismic Research Review,* Ponte Vedra Beach.

Gibson, R. G. and D. E. Norris (2002c), Long-range infrasound propagation modeling using updated atmospheric characterizations, *J. Acoust. Soc. Am.,* **112**, No. 5, Pt. 2, 2380.

Hedin, A. E, E. L. Fleming, A. H. Manson, F. J. Schmidlin, S. K. Avery, R. R. Clark, S. J. Franke, G. J. Fraser, T. Tsuda, F. Vial, and R. A. Vincent (1996), Empirical wind model for the upper, middle, and lower atmosphere, *J. Atmos. Terr. Phys.*, **58**, 1421-1447.

Norris, D. E. and R. G. Gibson (2002), InfraMAP enhancements: environmental/propagation variability and localization accuracy of infrasonic networks, *Proceedings of the 24th Seismic Research Review,* Ponte Vedra Beach.

Picone, J. M., A. E. Hedin, S. L. Coffey, J. Lean, D. P. Drob, H. Neal, D. J. Melendez-Alvira, R. R. Meier, and J. T. Mariska (1997), The Naval Research Laboratory program on empirical models of the neutral upper atmosphere, in *Astrodynamics: Advances in the Astronautical Sciences*, Vol. 97, edited by F. R. Hoots, B. Kaufman, P. J. Cefola, and D. B. Spencer, American Astronautical Society, San Diego, Ca.

Report to the Department of Defense on Infrasonic Re-Entry Signals from the Space Shuttle Columbia (STS-107) (2003), ed. by H. Bass, National Center of Physical Acoustics, University of Mississippi.